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Brightness of a capacitor discharge lamp (t_c, 16-25 μsec) has been extrapolated from determinations of the subjective attenuation of comparable durations upon square wave flashes from a glow modulator tube (R1131C). For the large field (61°) and high adaptation state (273 td), psychophysical integration of time and intensity (Bloch's Law) was found to hold only at durations less than 1.5×10^3 μsec. Examination of the manufacturer's data on lamp candlepower converted to trolands encourages the conclusion that large errors occur when the troland and other photometric quantities remain uncorrected for Bloch's Law effects which are found at short durations. A correct troland or adequate troland (td_a) is described.

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BRIGHTNESS OF A CAPACITOR DISCHARGE LAMP - BLOCH'S LAW FOR BRIEF FLASHES*

(Interim Report)

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ABSTRACT

BRIGHTNESS OF A CAPACITOR DISCHARGE LAMP - BLOCH'S LAW FOR BRIEF FLASHES

OBJECTIVE

The assessment of the brightness of capacitive discharge lamps requires special procedures. The intent of this work was to document such a procedure and, in the process, evaluate the adequacy of Bloch's Law for capacitive discharge and xenon lamps.

METHOD

Ten college students with normal vision determined the incremental threshold (Δ) for different exposure intensities and/or durations of capacitive discharge and xenon lamps. The procedure made the assumption that a barely noticeable increment in luminance is equal across intensity and duration.

RESULTS

The expression $td_e = L \times Se$ was evaluated to relate luminance (L) in candles per square meter and effective pupil area (Se) to effective trolands (td_e). Procedures are discussed for evaluating this expression in relation to specific conditions of experimentation and particularly the Grass PS2 lamp.

CONCLUSIONS

Candlepower figures provided by the manufacturer are not a direct measure of apparent brightness. Assessment of the physiological integration of luminous energy (I x t) for short flashes requires non-linear transformation according to the relation $\Delta I = 1.28 (\log t_c) + 7.28$ where t_c is the time constant of the flash exposure.

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BRIGHTNESS OF A CAPACITOR DISCHARGE LAMP -
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INTRODUCTION

Methods of experimental stimulation of the visual system have undergone few basic changes since Kepler. The usual method for delivery of light continues to be the interruption of a source by a shutter or similar device. Since 1950, two variations of direct, electronically controlled light sources have been commonly employed in vision laboratories--the glow modulator tube (Sylvania R1100 series) and the xenon filled, capacitive discharge lamp (Grass Instrument Company, PS2 series, photostimulator). The first can be varied both in intensity and duration, the second is operated over a small range of durations which vary with fixed steps of stimulus intensity. Intermediate values, if needed, are achieved by the application of neutral density filters.

The flash from the PS2 tube ranges between a time constant (t_c) of 16 and 25 μsec. The short time characteristic provides certain advantages which cannot be obtained by tungsten or xenon arc lamps. Electrophysiologically, the short duration minimizes the development of lateral inhibitory effects during the period of stimulation (1). Consequently, the neural events associated with it rarely show the "off effects" which may be seen at the termination of longer stimuli. The retinal image is highly stable, since eye movements can be presumed to be zero for the μsec duration of the stimulus. Further advantages which are of importance in pigment studies and in latency measurement of neural events accrue from the precision of timing and the ability to synchronize the discharge lamp to other pieces of equipment. Finally, the emission lines which compose the discharge spectrum are such that the color temperature of the xenon lamp approximates daylight with a significant amount of the energy emitted in the blue-green portion of the spectrum.

Recently, Boynton has reminded us that luminance (L) is an improper term when applied to most of the photometric measures (2). Abney's Law presumes that the superposition of lights of differing spectral composition produces a total experience in which the luminance of each light adds linearly. It is implicitly assumed that two lights or mixtures of lights which have equal luminance, as defined by Abney's Law, will be equally bright. The relationship between L, wavelength λ, and luminous efficiency V_λ assumes the general validity of Abney's Law. Boynton and Kaiser have argued that there are deviations from Abney's Law and its success is largely dependent upon the method by which it is demonstrated. Since, in the work to be reported, we have used a superposition technique which is probably least related to the prediction of luminance additivity, we will assume additivity failure and use the term brightness to describe the intensity dimension of our psychophysical judgments.

The brightness of stimuli whose t_c values are in the 10 to 100 μsec range is particularly difficult to determine by the methods which have been developed for stimulus sources with indefinite durations. Measures obtained with both the Macbeth Illuminometer and the Salford Electronic Instrument photometer are questionable when the unknown illuminant has a duration of less than 1 sec. Some reports of brightness measurement have been made where the flash rate was increased to near or above fusion. This method has promise, however, since the usual power supply used with xenon flash tubes does not maintain constant voltage or energy per discharge as the flash rate is increased. Also, high flicker rates age these lamps at an alarming rate.

Numerous authors have used capacitive discharge lamps and various estimates of their brightness (3-6). Most would admit that the stimulus intensity implied by the peak candlepower ratings (a megacandle or more) quoted for xenon discharge tubes must be moderated by consideration of intensity - time (I x t) integration effects in the human eye, though to what extent is obscure. Because of this, stimuli produced by xenon flash tubes are frequently considered "nonphysiological" or of such great brightness that saturation may be suspected. These ideas reflect the peak values provided by the manufacturer rather than judgments based upon the direct photometric measurement of the brightness of the tubes. The intent of the present work was to determine the brightness of a source with short t_c by an experimental method which accounts for the effects of I x t.

METHODS

It is not possible to measure directly the brightness of a capacitive discharge lamp. Therefore, a source (Sylvania R1131C glow tube) with variable t_c was measured directly by matching against the standard lamp of a Macbeth Illuminometer. Measures obtained for 1 sec and longer flashes were the same when tube peak current was maintained constant at 30 ma. Tube current determined the energy/unit time and within the time constants of the system (Fig. 1) set the peak output at a constant value. Only duration time of the square driving current was varied.

To measure brightness as a function of durations 1 sec and less, the increment threshold (Δ) for the glow tube output was determined. To do this, the source was superimposed upon the background field provided by a tungsten lamp (GE 1004 operated at 0.6 amp, 2650°K). The field and test stimulus, presented to the subject in Maxwellian view, both subtended a visual angle of 61°. The retinal illuminance of the background field was 273.4 trolands (td). Beginning with the 1 sec test stimulus whose brightness could be measured photometrically, ΔI values were determined for the test stimulus against the field (I) at durations from 1 sec (10^6) to 100 (10^2) μsec. Since peak energy (tube current) was held constant, and t_c set for each flash interval, ΔI changes with flash duration, achieved by filter attenuation, could be attributed to I x t effects.

With I x t effects specified for stimulus durations in the range of the capacitive discharge lamp t_c, it is possible to arrive at photometric brightnesses for the peak output values provided by the manufacturer. That is, if t_c, peak brightness, and attenuation (ϕt) due to I x t at t_c are known, brightness of the capacitive discharge lamp may be calculated. Peak brightness values are provided by the manufacturer, t_c may be measured directly, and ϕt is the subject of this inquiry. Further, if peak brightness values are changed by use of the lamp in another housing or lamps are purchased from another manufacturer, the ϕt values may be used to calculate brightness if the unknown illuminant is viewed concentrically with a field subtending 61° at 273 td, ΔI determined, and t_c measured.

The observer was seated before the ocular lens of the Maxwellian view system. Small cross hairs in the focal plane of the eye lens and a head and chin rest were provided to aid in proper alignment and to control fixation. The artificial pupil was 2 mm and, when properly viewed was focused in the plane of the pupil. Threshold ΔIs for the glow tube were obtained by the method of limits using both ascending and descending adjustments of the intervening counterbalanced neutral density filters. Similarly, ΔI measures were made for the xenon discharge lamp at its five electronically controlled intensities (1, 2, 4, 8, and 16). Ten college students with normal vision served as observers in the glow tube determinations. Three of these students later determined the ΔIs for the xenon lamp. No difficulty was experienced in the making of incremental threshold judgments or in holding proper fixation.

RESULTS

Figure 1 describes the waveform characteristics for both glow tube and the xenon capacitive-discharge flashes. It appears that line capacitance became a significant factor in the decay of the glow tube output at short durations. The replicability of the glow tube output was good. Each of the records is the result of three superpositions of the same stimulus. Only in the 150 μsec stimulus is there a suggestion that more than a single repetition was recorded. The energy-time measures (Fig. 1A) were made with a Texas Instrument light diode, t_c = 20 nanosec. Both detectors were suitably buffered. The xenon discharge lamp output curves (Fig. 1B) are characteristic of a capacitive discharge function. The time constants of these stimuli range from 16 μsec for the least bright stimulus, "1", to 25 μsec for the brightest setting, "16." Other values varied between 16 and 18 μsec. Like the glow tube measurements, each record in Figure 1B is the superposition of three flashes. Flash amplitudes have been normalized so that temporal characteristics could be evaluated. The attenuations necessary to maintain a constant signal amplitude between the five electronic intensity settings of the xenon lamp were 0.4 log units to equate intensities 2 and 1, 0.33 log units to equate settings 4 and 2, 0.61 log units to equate settings 8 and 4, and 0.51 log units to equate settings 16 and 8. The average increase was 0.46 log units for each step increase in electronic intensity.

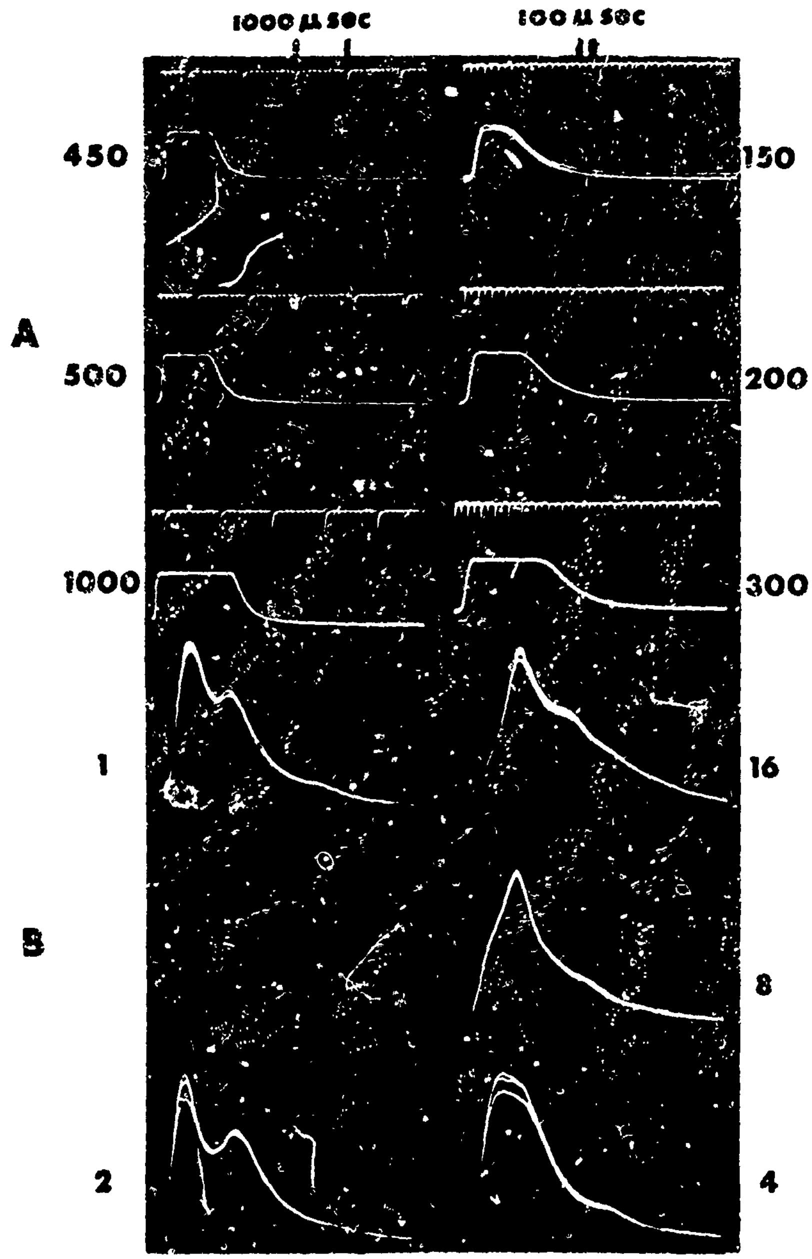

Fig. 1. Time characteristics of the lamps. All records are superpositions of three flashes. A. Glow tube (Sylvania R1131C) response to square wave driving signal. Numeral notations in the margins indicate the time set into the signal generator. Time marks measure true flash duration; 10^3 and 10^2 μsec, left column; 10^1 and 5 x 10^1 sec, right column. B. Xenon capacitive-discharge wave configurations. Time axis divisions are 5 μsec. Marginal numbers are power settings for the Grass lamp driver. Adjustments were made to make amplitudes similar between intensities.

Figure 2 shows the relationship between stimulus duration in microseconds and the increment threshold for the glow tube stimulus with the field at 273.4 td. Extrapolation of the linear fit for durations from 10^2 to 10^3 to values less than 10^2 µsec is supported by Brindley's (7) results. The composite function shown in heavy line in Figure 2 gives the subjective attenuations for t_c values between 1 sec (10^6) and 20 ($10^{1.3}$) µsec for an "average" observer.

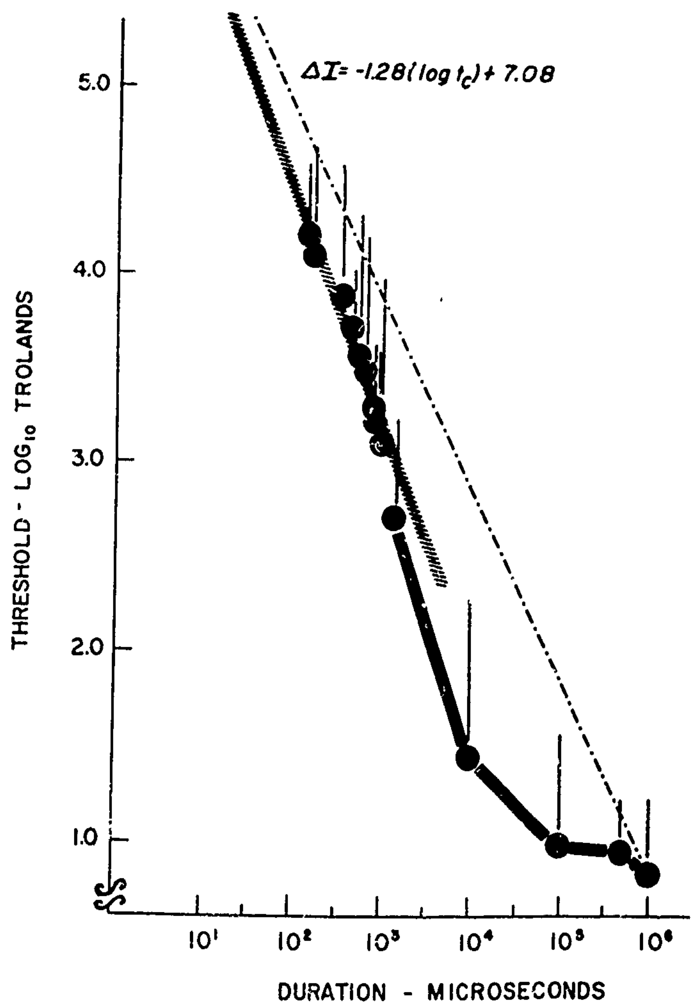

Fig. 2. Increment threshold of a stimulus at various durations referenced to a 61° white light (2650°K) at 273 td. Extension of the chart line to 10 µsec was by extrapolation based on work by Brindley (7). The regression equation describes only the data between 10 and 10^3 µsec, where ΔI is in log td. The vertical lines describe + one standard deviation. The interrupted line describes a linear correction like the td-sec.

The average increment threshold for stimuli 1 sec or longer was 0.87 log td. From the regression equation (Fig. 2) 5.41 log td would be required for ΔI when the duration was shortened to t_c = 20 μsec. Thus, the subjective attenuation of a glow tube set for t_c = 20 μsec due to I x t factors was determined to be (5.41 - 0.87) = to 4.54 log td.

When the xenon discharge lamp was substituted for the glow tube in the Maxwellian view optical system, at its lowest intensity "1", ΔI was achieved with 3.21 log density units attenuation. By definition, the retinal illumination produced by the xenon lamp at this setting, minus 3.21 log units, was ΔI and was equal to 0.87 log td. The unattenuated flash luminance in td was the ΔI quantity plus the attenuation required to achieve it (0.87 + 3.21 = 4.08 log td). The xenon lamp, in Maxwellian view, produced the illumination values 4.45, 4.81, 5.42, 5.93 log td at settings 2-16.

DISCUSSION

Earlier research on the stimulating effects of light and the interaction between intensity and time variables is clustered between the years 1885 and 1935. Papers by Brindley (7,8) have reviewed this literature and extended the findings to stimuli with t_c = 0.41 μsec. However, in the region from 1000 to 0.˜ μsec, fewer than five datum points have been sampled in all of the literature with fewer than three subjects contributing to any point. Recently, interest in some visual research quarters has swung toward the stimulating effectiveness of flash durations in the 100 μsec range (9,10). We undertook this research to provide additional information on variability of the ΔI judgment and the impact of I x t upon ΔI in this time region.

The methodology which has been used in this experiment is not unusual and was employed earlier by Barlow (11) in a series of experiments which related stimulus area and temporal summation in the human retina. Barlow's stimulus at 5.9° of visual angle is the largest employed in research which encompassed both brief stimuli and ΔI measurement. Barlow also examined the summating effects of stimulation in graded smaller areas. His findings are particularly valuable since they demonstrate the interaction between area and time. We selected a very large visual angle because this circumstance has been more commonly reported in the literature, both by researchers who have stimulated with lamps directly viewed and by those who are interested in flashblindness. The area of Brindley s (7) bipartite field approaches ours, but the psychophysical judgment required by his method departs from that required for the production of ΔI judgment.

The line slopes for a plot of stimulus area and threshold appear to be nearly parallel (11; Fig. 3), and an increase by one order of magnitude in area is associated with about a one log unit decrease in the ΔI value. After the stimulus area increases beyond 0.5° square, the function slowly becomes asymptotic. Only for high background intensities

at Barlow's shortest duration (8.5 msec) did there appear a clear symptote for critical duration at a stimulus area of 28 square degrees. It seems likely that summation does not increase past 10° stimulus angles.

Except for the concentration of data at times less than 10^3 μsec, and the large visual angle, the data described by Figure 2 are similar to other data which have been reported. The number of subjects was about five times greater than is normally used and made possible the calculation of a variance measure. Further, the time region in which complete reciprocity was seen was shorter than those previously reported (12). This is probably the result of combined effects from the relatively high adaptation intensity, the very large retinal angle, and the additivity of these effects, as suggested by Barlow. Graham and Margaria (13) reported failure of intensity time reciprocity for stimuli as short as 2×10^3 μsec. Our measures show loss of reciprocity of brightness and duration for stimuli greater than 10^3 μsec. But it is difficult to determine the exact point of failure. The change may be more abrupt than previously reported for similar stimuli and lower adaptation levels (14). Since the function is monotonic only at short durations it is not described fully by the popular td-sec (see Fig. 2) or by the general linear correction proposed by Cobb and Morton (15). If the data in Figure 2 are included in an f ratio test of reciprocity at an alpha level of 0.05 (analysis of variance one way repeated measures), the ratio remains insignificant as points are added, moving to the right on the (Fig. 2) abscissa until the point at 10^4 μsec is included. Including this point produces a significant f ratio. It appears that reciprocity is lost in the time region 10^3 to 10^4 μsec. It is probable that the first deviation from Bloch's Law for these data occurs at about 10^3 μsec. The degree of deviation inserted by the 10^3 μsec datum point relative to the high stability of the line fit of the preceding points probably is insufficient to produce statistical significance. If it is real, the abruptness of the shift at 10^3 μsec is interesting and may have been forecast in the work by Barlow, where some rather large deviations may be seen after his threshold curves departed from the slope of -1. The dramatic nature of the shift seen in Figure 2 may be magnified by the effects of high adaptation level and large angular subtense.

The validity of these data depends primarily upon the acceptability of indirectly matching two stimuli by way of a third stimulus. This is an acceptable technique if it can be demonstrated that the colors of the three lights are not greatly different. A comparison of the color temperature of three lamps is depicted in Figure 3. Viewed directly, suprathreshold, the xenon lamp appeared to be white with a small blue content, the glow modulator tube appeared white but with a small blue-yellow content, and the tungsten adapting field appeared to be white with a very small yellow component. Hue was never detected in the ΔI determinations which are colorless even with highly saturated stimuli (16-18). We believe that color temperature difference in our lamps does not serve to invalidate the results. The color temperature differences remained constant. If an error occurred as a result of the weighting in

the yellow of the tungsten lamp, the error would be in the direction of increasing the relative brightness of the xenon lamp. A more interesting feature of the finding was the perceived dimness of the xenon lamp. Increment threshold values from Steinhardt (19) agree with ours where I = 273 td. If serious errors in ΔI were caused by stimulus color temperature differences, such good agreement would be unlikely.

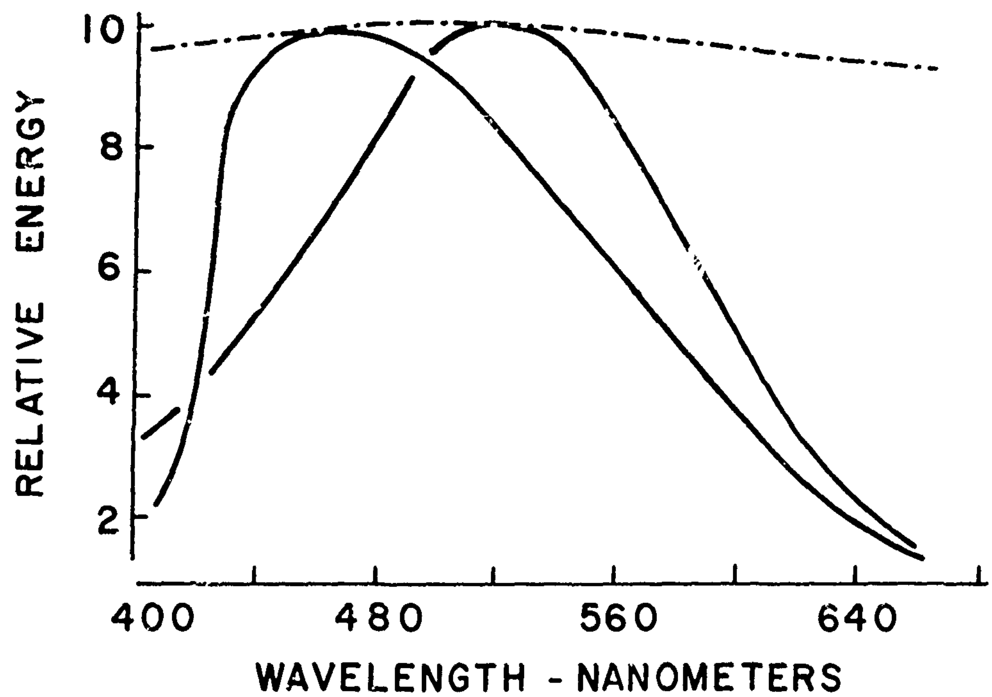

Fig. 3. Spectral distributions of energy in the visible spectrum for three lights. Sylvania R1131C glow tube at 30 ma current (peak at ∿ 520 nm); Grass Instrument PS2 xenon flash lamp (peak at ∿ 450 nm); 6000°K blackbody (dashed line). An infrared blocking filter eliminated all energy above 850 nm in the measures on the xenon lamp. Data have been smoothed to eliminate some sharp spectral lines which appeared in the xenon curve. Their energy is included in the smoothing.

The evaluation of the photometric brightness of a capacitive discharge xenon lamp may be used to clarify the stimulating value of the Grass PS2 system or other systems rated in (peak) candlepower. The Grass system consists of the lamp, a parabolic reflector, a housing and power supply, and trigger unit. Several authors have used the PS2, directly viewed, without additional optics in experiments on cortical evoked responses and electroretinograms (20,21), and it is used routinely in electroencephalography.

The manufacturer states that the maximum light output from the system is 1.5×10^6 candlepower, instantaneous peak, in the central beam which is easily identified as a brighter area of homogeneous illumination which has a radius of about 15 cm when viewed on a reflecting surface 60 cm from the lamp. Since candlepower is luminous intensity expressed in candelas (cd) (22) luminance of the central beam at maximum intensity is 1.5×10^6 cd/m^2. For an observer, effective retinal illumination may be calculated from the luminance in cd/m^2 by

$$td_e = L \times Se \tag{1}$$

where td_e is effective trolands, L is luminance in cd/m^2, and Se is the effective pupil area. Se includes a correction for the relative directional efficiency (Stiles-Crawford effect) of stimulation through a pupil of some diameter d. The formula:

$$Se = 1/4\pi d^2[1 - 0.085(d^2/8) + 0.002(d^2/48)] \tag{2}$$

was suggested by LeGrand (18).

Most research utilizing the PS2 system has used subjects at a high mesopic adaptation state, around 10 cd/m^2. According to Reeves (23), this level would result in about a 4 mm pupil. Substituting this value into equation [2], the value Se = 10.30 mm^2 is obtained. Then solving for td_e in equation [1]

$$td_e = (1.5 \times 10^6)\ (10.30)$$

$$td_e = 15.4 \times 10^6$$

the peak retinal illumination may be found for maximal intensity setting of the PS2 system. Since this does not differ greatly from the luminance of the solar disc (18, p. 82) it may be suspect. The peak value cannot be treated as though it has indefinite duration. The psychophysical experiment described in this report requires that brightness be adjusted for stimuli where the time constant is $<$ 1 sec. The proper correction, from Figure 2 (t_c = 20 μsec), is a reduction of the peak by 4.54 log units (from Fig. 2 ΔI at t_c = 1 sec is 0.87 log td; ΔI at t_c = 20 μsec is 5.41 log td; 5.41 - 0.87 = 4.54). This includes the assumption that the peak luminance rating and the luminance measured from the same source during an exposure $\geq$ 1 sec would be the same. The td_e corrected for I x t effects might be called the <u>adequate troland</u> (td_a).

Table 1 lists the td_e and td_a values calculated for the Grass PS2 lamp and housing assembly, as purchased. The brightness of stimuli of other time constants less than 10^3 μsec may be calculated using equation [3] which requires an attenuation factor (ϕt) which corrects for I x t effects arising from the psychophysical impact of the light's time

constant. For photopic adaptation states, ϕt is the difference between the ΔI value for the 1 sec stimulus duration (0.87 log td) and the ΔI value for the appropriate stimulus t_c from Figure 2, where I = 273 td. td_e should be calculated from equation [1].

$$td_a = td_e - \phi t \quad [3]$$

TABLE 1

Values of td_e and td_a for the Grass PS2 Lamp Viewed Through a 4 mm Pupil

Intensity Setting	Rated Peak Luminance (Candlepower)	Effective Trolands (td_e)	Adequate Trolands (td_a)
1	9.0×10^4	9.27×10^5	27
2	1.8×10^5	1.85×10^6	55
4	3.7×10^5	3.81×10^6	114
8	7.5×10^5	7.72×10^6	232
16	1.5×10^6	1.54×10^7	460

Another simple method, based upon this research, may be used to measure the photometric result of a brief flash where peak candlepower is unknown. It is an adaptation of the measures used to develop Figure 2. In the absence of an optical system the observer should be seated before a neutral white tangent screen which is observed through a 2 mm artificial pupil. A steady white adaptation light should be provided to illuminate the screen uniformly with the beam axis at a known angle to the screen. The angle should be no more than 30° from the perpendicular. The flash source should be placed to subtend the same angle. Reflectance of the screen may be measured by the difference between its surface luminance and the luminance of a Macbeth Illuminometer test plate (reflectance specified) held at the same distance from the adapting light. The surface luminance of the screen may be adjusted to produce 273 td calculated from equation [1]. The observer must determine ΔI for the flash source by varying its intensity with neutral filters until its impact upon the luminance of the screen at 273 td is just noticeable. The value for ΔI under ideal conditions at t_c values $\geq$ 1 sec is 0.87 log td, from Figure 2. Since the measures were made psychophysically, the ΔI value (0.87 log td), corrected for the neutral density required ($\log_{10}$ units) between the lamp and the tangent screen, will be in the retinal

illumination units, td_a available with the lamp output unattenuated. That is, td_a of the secondary source equals attenuation of primary source (log density) to achieve ΔI where $t_c < 10^3$ µsec plus ΔI where $t_c > 1$ sec. Retinal illumination may be calculated for the lamp as a primary source by correcting for Lambert's Law scatter from the tangent screen as described by LeGrand (18).

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